Radiolarian biostratigraphic constraints on the generation of the Nidar ophiolite and the onset of Dras arc volcanism: Tracing the evolution of the closing Tethys along the Indus – Yarlung-Tsangpo suture

Sergey V. Zyabrev[1], Satoru Kojima[2], and Talat Ahmad[3]
[1]*Institute of Tectonics and Geophysics, Kim Yu Chen St., 65, Khabarovsk, 680000, Russia.*
[2]*Department of Civil Engineering, Gifu University, Gifu 501-1193, Japan*
[3]*Department of Geology, University of Delhi, Chatra Marg, Delhi 110007, India*
email:shibutani.susumu@sumicon.co.jp
[2] *Department of Earth Sciences, Faculty of Science, Ehime University, 790-8577 Japan*
email: sziabrev@graduate.hku.hk

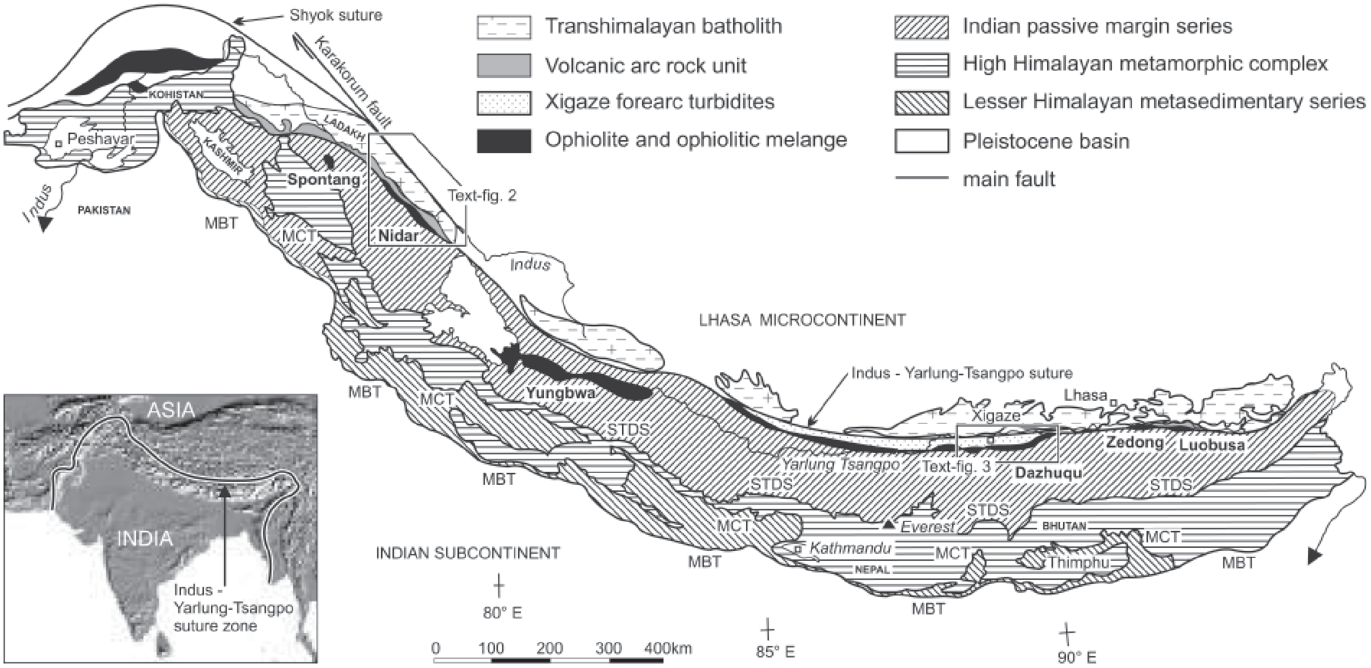
ABSTRACT: The Nidar ophiolite in Ladakh Himalaya is a substantial fragment of oceanic lithosphere preserved along the western continuance of the Indus – Yarlung-Tsangpo suture zone. It was generated in a supra-subduction zone setting and is linked in development to the Dras intra-Tethyan volcanic arc. Earlier reported Hauterivian – Aptian radiolarians from the volcano-sedimentary succession atop the ophiolite were used to constrain the age of the ophiolite and duration of arc volcanism. Re-assessment of radiolarian taxonomy and biostratigraphy reveals an upper Barremian to upper Aptian range for the Nidar volcano-sedimentary section, the same as for the marine sedimentary cover atop the Dazhuqu ophiolite in the southern Tibet. The lower limit of its stratigraphic range places a minimum temporal constraint on the Nidar ophiolite generation in the late Barremian (ca 126 Ma). This compares well with radiometric age for the ophiolite (124± 1 Ma). The sedimentary successions of both ophiolites bear resemblance in the record of associated arc volcanism. Dras arc volcanism in the Nidar section began in the early Aptian. The Nidar and Dazhuqu ophiolites are interpreted as distal chronological equivalents developed in association with the same intra-Tethyan subduction system. Parallels between the evolution of this Cretaceous intra-Tethyan subduction system and other systems in the region remain uncertain.

INTRODUCTION

The Indus – Yarlung-Tsangpo suture (text-fig. 1), a locus of the India-Asia collision (Gansser 1964, 1977; Dewey and Bird 1970), marks where the previously vast Tethys eventually closed in the course of India-Asia convergence, through north-directed subduction of oceanic lithosphere. Much of the Tethyan interior was subducted and further obliterated during the collisional tectonism. The present day mosaic of Tethyan remnants or terranes within the suture represents a miniscule fraction of what was built somewhere within a wide oceanic expanse that once separated India from the rest of Asia. Study of these terranes provides crucial insight into the architecture and evolution of Tethys, yet such study is complicated by fragmentary preservation and disrupted original disposition of terranes as well as a scarcity of data. In particular, the sequence of events that accompanied the closure of Tethys is not well constrained and appears dissimilar along the length of the suture. The widely accepted model for the Tibetan sector of the suture (Searle et al. 1987) assumed subduction of the entire north-south extent of oceanic lithosphere along the southern margin of Asia. This contrasted to the evolutionary scenario for the areas further west, Kohistan and Ladakh, where the presence of volcanic arcs associated with intra-Tethyan subduction is well documented (Searle et al. 1987; Searle et al. 1999; Corfield et al. 2001). Although recognition of an intraoceanic subduction system in the central part of the Yarlung-Tsangpo suture (Aitchison et al. 2000; Aitchison et al. 2002; McDermid et al. 2001, 2002; Van der Voo et al. 1999) has called into question previous oversimplified models, correlation of tectonic units and events remains ambiguous. One of the key issues pertaining to this correlation and evolution of the Tethys is the timing of the generation of ophiolites and onset of the associated arc volcanism preserved along the suture. In this paper we reassess radiolarian-based ages for the volcano-sedimentary sequence of the Nidar ophiolite, Ladakh Himalaya, northern India. This places higher-precision temporal constraints on the ophiolite generation and onset of the associated Dras arc volcanism, and permits for a better correlation of the Nidar ophiolite with the Dazhuqu ophiolite, southern Tibet.

GEOLOGICAL FRAMEWORK

Ophiolitic massifs and mélanges form an ophiolitic belt intermittently traceable along the Indus – Yarlung-Tsangpo suture (text-fig. 1; Nicolas et al. 1981; Burg and Chen 1984; Girardeau et al. 1984; Wang et al. 1987; Aitchison et al. 2004). Although most ophiolitic bodies are confined to the suture, several of them lie some few tens of kilometers to the south being thrust over the Indian passive margin. Some ophiolitic massifs within the belt represent substantial fragments of oceanic lithosphere. Although tectonically disrupted, they display a complete succession from a mantle portion to marine sedimentary cover atop pillow basalts. Several ophiolites occur with volcanic rocks of island arc affinity and/or are characterized by petrologic and geochemical signatures pointing to their origin in a supra-subduction zone setting. Radiometric ages from ophiolitic rocks along the length of the suture (table 1) indicate ophiolite generation from the Middle Jurassic to Early Cretaceous. Age variations within some massifs probably reflects different episodes of heir development. In comparison, radiolarian-based ages of the ophiolites along the suture have been relatively scarce. Here we review radiolarian biostratigraphy for the mid-Cretaceous marine sedimentary successions of the Nidar and Dazhuqu (Xigaze) ophiolites (Kojima et al. 2001; Ziabrev 2000; Ziabrev et al. 1999; Ziabrev et al. 2003) and show how these data greatly improve correlation and age determination.



TEXT-FIGURE 1
Distribution of ophiolites and main tectonic units within and bounding the Indus – Yarlung-Tsangpo suture zone. Modified from Geological Map of Xizang (Tibet) Autonomous region, PRC (BGMRXAR, 1993) and figures by Le Fort (1996) and Yin and Harrison (2000). Inset shows a trace of the suture zone. Abbreviations: STDS – South Tibet detachment system, MCT – Main Central thrust, MBT – Main Boundary thrust.

Nidar ophiolite is a large fragment of oceanic lithosphere (text-fig. 2) preserved along the western continuance of the suture in the Ladakh Himalaya, northern India (Thakur and Misra 1984; Kojima et al. 2001; Sachan 2001). The ophiolite and underlying Zildat ophiolitic mélange are thrust south-westward over the Indian Plate. The northeastern contact is a northeast-directed thrust that places it over the Tertiary Indus Molasse that onlaps the Ladakh plutonic complex. The ophiolitic pile faces northeast and exhibits an almost complete succession from the upper mantle to marine pelagic deposits. Its crustal section consists of foliated gabbros (100 m) and well-developed dykes, crosscutting massive gabbros (500 m), and overlain by 500 m of pillow lavas and radiolarites (Mahéo et al. 2004). Geochemical studies indicate ophiolite generation in a supra-subduction zone setting (Ahmad et al. 2008; Kojima et al. 2001; Sachan 2001; Mahéo et al. 2004) ^{39}Ar/^{40}Ar ages on hydrothermal amphibole from gabbros range from 100 to 124 Ma (Mahéo et al. 2004). Sm–Nd whole-rock ages of 140.5±5.3 Ma (Linner et al. 2001) and 139.6±32.2 Ma (Kojima et al. 2001; Ahmad et al. 2008) have been obtained from the gabbros. In the Nidar section, an upper volcano-sedimentary member is ~300 m thick (text-fig. 4) and comprises chert, siltstone, volcanomictic sandstone, tuff, and volcanic/volcaniclastic rocks, with the clastic component increasing in volume up-section (Kojima et al. 2001). It is in a fault contact with ophiolitic gabbro at the bottom of the section. Lithologies and geochemical signature of volcanic rocks indicate an intra-oceanic island arc setting (Kojima et al. 2001; Ahmad et al. 2008). Volcanic and volcaniclastic rocks of this succession correlate with the Dras arc rocks to the north-west (Thakur and Misra 1984) and likely record the onset of arc volcanism. Late Valanginian-Hauterivian to Aptian radiolarians (text-fig. 5) were used to constrain the age of the ophiolite and duration of arc volcanism (Kojima et al. 2001).

Dazhuqu (Xigaze) ophiolite (text-fig. 3) is the best known ophiolite in the southern Tibet because of thorough studies following the Franco-Chinese expedition to this area in the early 1980s (Nicolas et al. 1981, Girardeau et al. 1984; Girardeau et al. 1 985a, 1 985b; Wang et al. 1987). To the south of Xigaze, several individual ophiolitic massifs form a nearly continuous outcrop over 170km long and up to 25km wide (text-fig. 3). A pile of ophiolitic rocks is thrust northward over the Cretaceous Xigaze forearc basin, and southward over the Bainang accretionary complex (Burg and Chen 1984; Wang et al. 1987). Where the ophiolite is juxtaposed against the Indian passive margin series, its southern contact is the north-directed thrust with Indian Plate rocks in the hanging wall. Ophiolitic sections are mostly north facing and partially repeated across strike-slip faults. Tectonically attenuated, they locally display a complete ophiolitic sequence from Cr diopside-rich harzburgites in the south to marine sedimentary cover on mafic volcanics in the north (Nicolas et al. 1981, Girardeau et al. 1984; Girardeau et al. 1985a, 1985b; Wang et al. 1987). Nicolas et al. (1981) interpreted the origin of the ophiolite underneath a slow spreading ridge. On the basis of detailed geological, mineralogical and petrochemical study the ophiolite has been recently re-interpreted as having originated in an intra-oceanic supra-subduction zone setting (Aitchison et al. 2000; Aitchison et al. 2002; Aitchison et al. 2004; Hébert et al. 2000; Hébert et al. 2001). Paleomagnetic data show that the ophiolite formed at equatorial to very low northern latitudes (Abrajevitch et al. 2005).

A U-Pb whole-rock radiometric age of 120±10 Ma for the ophiolite was reported from the Xigaze area (Göpel et al. 1984). Albian – early Cenomanian radiolarian-based ages are known for the marine siliceous and fine-grained volcaniclastic deposits overlying mafic ophiolitic rocks (Marcoux et al. 1982; Li and Wu 1985; Wu 1986). New data on lithostratigraphy and radiolarian biostratigraphy have been obtained for several sedimentary sections depositionally overlying ophiolitic basalts (Ziabrev 2002; Ziabrev et al. 1999; Ziabrev et al. 2003), five of which are considered herein (text-fig. 4). Overall, the sedimentary succession exhibits a coarsening-upward trend from chert and siliceous mudstone to volcaniclastic turbidites and includes basaltic agglomerate and felsic tuff, which indicates an island-arc depositional environment. Well preserved and abundant late Barremian to late Aptian radiolarians (text-fig. 6) have been recovered from various lithologies. Detailed biostratigraphic study of these assemblages has yielded high-precision age constraints on the timing of the eruption of ophiolitic basalts, indicating that ophiolitic rocks in the Xigaze area were generated from late Barremian to mid-Aptian (Ziabrev 2002; Ziabrev et al. 2003).

BIOSTRATIGRAPHIC DATA, METHODOLOGY AND RESULTS

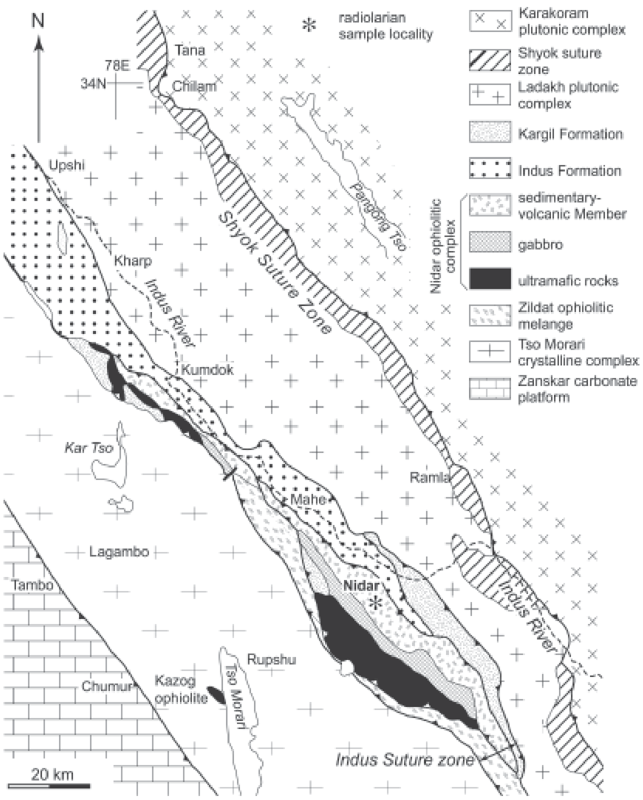
The radiolarian biostratigraphic data used herein for correlation of the ophiolitic sedimentary sections were acquired in the course of litho- and biostratigraphic investigations of the Nidar (Kojima et al. 2001) and Dazhuqu (Ziabrev 2002; Ziabrev et al. 1999; Ziabrev et al. 2003) ophiolites. Standard techniques of radiolarian extraction with diluted hydrofluoric acid (Pessagno and Newport 1972) and subsequent sorting, mounting and SEM imaging were implemented. All the fossil material reported here is deposited in the Nagoya University Museum (Nidar section) and in the Department of Earth Sciences, The University of Hong Kong (Dazhuqu sections). For the Nidar section, data were updated with additional occurrences of radiolarians to improve stratigraphic resolution. The taxonomy used by Kojima et al. (2001) has been revised and updated to ensure consistency with current systematic nomenclature and biostratigraphic knowledge (Jud 1994; O'Dogherty 1994; O'Dogherty and Guex 2002).

The updated and revised dataset for the Nidar ophiolite was combined with the dataset for the Dazhuqu ophiolite (table 2) in order to facilitate direct correlation of their sedimentary successions. We re-calibrated these data to the radiolarian range chart for the Tethyan regions (O'Dogherty and Guex 2002) by means of the Unitary Association method (Guex 1991). The combined dataset (in the form of numerically coded taxa) was processed together with a robust dataset for the Tethyan regions (O'Dogherty and Guex 2002) using BioGraph computer program (Savary and Guex 1999). During the algorithm execution, the program constructed a new succession of 60 unitary associations (UA) with seven new UAs in addition to the 53 UAs of O'Dogherty and Guex (2002). Only the Barremian-Aptian portion of this succession (UA30 – UA48) is used herein. The accompanying correlation chart enabled the detailed correlation between the sections (text-figs. 4, 7). Biostratigraphic data are correlated to the chronostratigraphic scale of Gradstein et al. (2004).

The data re-calibration reveals an upper Barremian – upper Aptian stratigraphic range for the Nidar section (text-figs. 4, 7), the same as for the marine deposits in the Dazhuqu ophiolite (Ziabrev 2002; Ziabrev et al. 2003). Given the Nidar section is tectonically truncated at the bottom (Kojima et al. 2001), the lower limit of its stratigraphic range places a minimum temporal constraint on the timing of the ophiolite generation in the late Barremian.

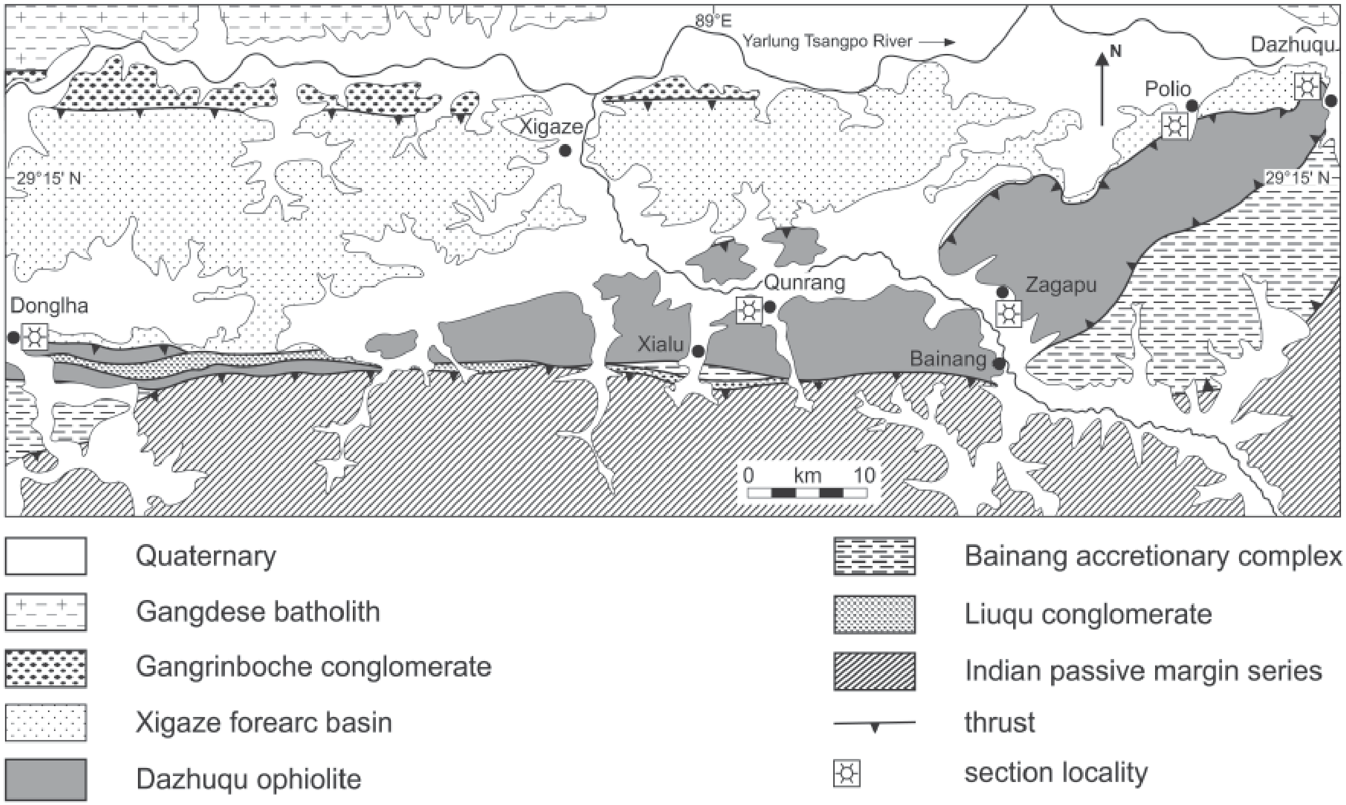
TIMING OF THE NIDAR OPHIOLITE GENERATION AND DRAS VOLCANISM ONSET

Our biostratigraphic results help to constrain the timing of the Nidar ophiolite generation and onset of arc volcanism. Although the Nidar section is tectonically truncated at the bottom, it is remarkably thick and the temporal range of its accumulation covers a period of ~12 myr (text-figs. 4, 7). Only minor portion of the section seems to be eliminated due to faulting, and the late Barremian age (ca 126 Ma) for its lower portion compares well with the $^{39}Ar/^{40}Ar$ age 124±1 Ma for the ophiolitic gabbro (Mahéo et al. 2004; table 1). It also does not conflict with the whole-rock Sm–Nd age of 139.6±32.2 Ma for the gabbro (Kojima et al. 2001; Ahmad et al. 2008; table 1). The age of the Nidar ophiolite is likely to be late Barremian, and it is entirely possible that both the Nidar and Dazhuqu ophiolites are distant chronological correlatives developed in association with the same intra-Tethyan subduction system. Both Nidar and Dazhuqu sedimentary successions bear resemblance in the record of arc volcanism (text-fig. 4), yet the Dazhuqu ophiolites is not linked with any arc fragment. This might be due to a low preservation potential of arcs during the collisional tectonism (Chemenda et al. 2001; Boutelier et al. 2003).



TEXT-FIGURE 2
Simplified geological map showing distribution of Nidar ophiolitic rocks near Nidar (modified from Ahmad et al. 1996) and locality of the section studied.

Extrusive volcanism in the Nidar section began by the early Aptian (ca 124 Ma, text-fig 4, 7). Extrusive rocks intercalated within the volcano-sedimentary member of the Nidar ophiolite are basalt, andesite and rhyolite (Bagati and Kumar 1999; Ahmad et al. 1998; Ahmad et al. 2005; Kojima et al. 2001, Mahéo et al. 2004). Petrochemical study reveals their boninitic and arc tholeiitic affinities (Ahmad et al. 1998). Multi-element and REE patterns for volcanic rocks indicate an island arc-related tectonic setting (Ahmad et al. 2005; Mahéo et al. 2004). The characteristics of the Nidar volcanic rocks are similar to those of the ophiolite maturity stage by Shervais (2001).



TEXT-FIGURE 3
Simplified geological map showing distribution of Dazhuqu ophiolitic rocks near Xigaze (modified from Wang et al. 1987) and localities of the sections studied.

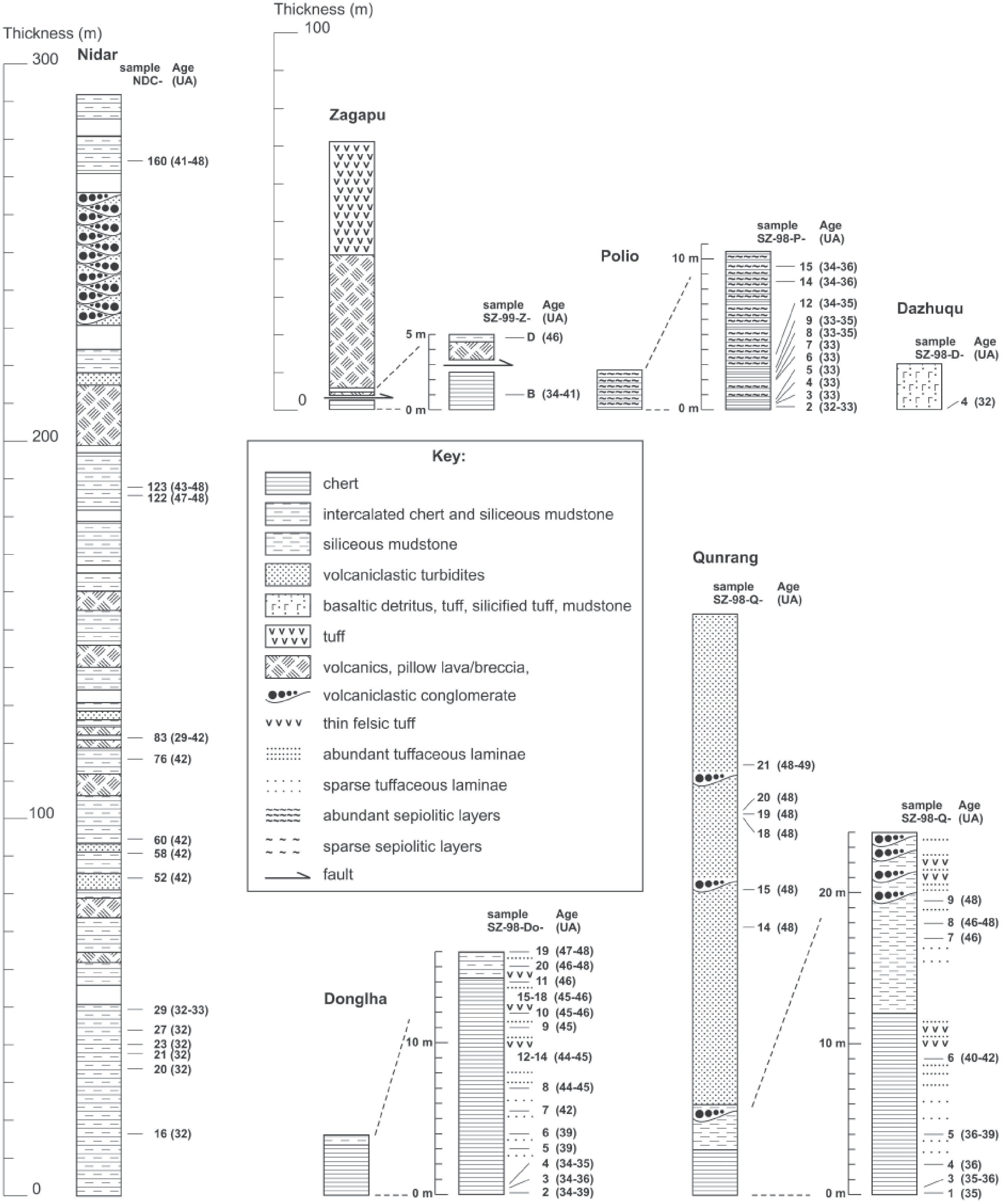
The Nidar volcanics are correlated with the Dras arc volcanics in the western Ladakh (Thakur and Misra 1984). They share similar geochemical and REE patterns with the Dras volcanics and related sediments (Dietrich et al. 1983; Clift et al. 2000) and the Chalt volcanics in Kohistan, northern Pakistan (Khan et al. 1997). The first appearance of volcanics in the Nidar section most likely records the onset of the Dras volcanism in the early Aptian. This is a higher precision constraint on the initiation of island arc volcanism than previous estimates that cover a wide age range: Late Jurassic (Dietrich et al. 1983; Honegger et al. 1982), Early Cretaceous (Clift et al. 2000), Hauterivian (Kojima et al. 2001) Aptian-Albian (Rolland et al. 2002), and Albian-Cenomanian (Reuber 1989; Rolland et al. 2000).

The volcanism ceased after the Dras (Kohistan – Dras) arc docked with Asia along the Shyok suture zone. Suturing occurred during the Campanian-Maastrichtian (Robertson and Degnan, 1994), and was completed by 75±1 Ma (Treloar et al. 1989); it is bracketed between 95 and 75 Ma (Searle et al. 1999) or ca 75–65 Ma (Clift et al. 2000). Based on early estimates for the initiation of arc volcanism Clift et al. (2000) noted that the arc was active for ~65 myr, somewhat longer than the 45 myr of activity recorded in the modern western Pacific (Hussong and Uyeda 1982). In the light of our data, the duration of the Dras volcanism is narrowed down to a maximum period of 40 myr, which better fits with the account of modern intraoceanic arc evolution.

CORRELATION WITH OTHER TETHYAN OPHIOLITES AND ARC FRAGMENTS

The interpretation of the Nidar and Dazhuqu ophiolites as remnants of the same intra-Tethyan subduction system allows for further hypothesizing on the architecture and evolution of the Tethyan floor. The Dazhuqu ophiolite (in a broad sense, including the ophiolitic massifs at Xigaze, Zedong and Luobusa) was formerly linked in its development to the Zedong intraoceanic island arc previously regarded as Early Cretaceous (Aitchison et al. 2000; McDermid et al. 2001). Subsequently, U-Pb ages of between 157 – 163 Ma and ^{39}Ar/^{40}Ar ages of between 154 – 159 Ma for Zedong arc rocks, and Bathonian – early Callovian (ca 160 – 169 Ma) radiolarian-based ages for the underlying chert (McDermid 2002; McDermid et al. 2002), as well as Sm-Nd age of 177±31 Ma for the Luobusa ophiolite (Zhou et al. 2002), revealed notably older, Middle to early Late Jurassic ages of these units (table 1). Although all contacts between them are faulted and their original relationship is undetermined (Aitchison et al. 2004; McDermid 2002; McDermid et al. 2002), they likely formed as components of the same Middle to Late Jurassic subduction system that evolved long before the generation of the mid-Cretaceous Dazhuqu ophiolite cropped out in the Xigaze area.

The presence of the supra-subduction zone ophiolites of different ages led Aitchison et al. (2004) to suggest that remnants of more than one intra-oceanic island arc are preserved between India and Asia. The structural relationships of these ophiolites along the Tibetan sector of the suture remain ambiguous (Aitchison et al. 2004), and their original disposition within the Tethys is obscure. Chronological correlation of the Nidar and Dazhuqu ophiolites may provide some lead to solving this enigma. With the re-assessed age of the Nidar ophiolite, the ophiolites along the suture are segregated into the two groups of discretely different ages: mid-Cretaceous and Middle to Late Jurassic. The latter



TEXT-FIGURE 4
Sedimentary sections overlying the Nidar and Dazhuqu mafic ophiolitic rocks showing the positions of samples and their correlation with Unitary Associations (UA) modified from O'Dogherty and Guex 2002. Details of some sections or their lower portions are shown at a larger scale on the right.

group includes the Luobusa (177 ± 31 Ma, Zhou et al. 2002), Yungbwa (147±25 Ma and 152±33 Ma, Miller et al. 2003), and Spontang (177±1 Ma, Pedersen et al. 2001) ophiolites (table 1). Both the Yungbwa and Spontang ophiolites represent tectonic outliers that were thrust over the Indian passive margin series and occur several tens of kilometers south of the suture. Their present-day position relative to the mid-Cretaceous Nidar ophiolite and some others confined to the suture (Miller et al. 2003) probably reflects their original disposition on the Tethyan floor. As the simplest interpretation, one could envisage similar original relationships of the ophiolites for the entire length of the Indus – Yarlung-Tsangpo suture. And this could be the case if the ophiolites belong to the two distinct subduction systems. However, the different origin inferred for the ophiolites (underneath a mid-ocean ridge vs. above a subduction zone) and their association with island arc segments of different ages make any simple tectonic interpretation impractical. Thus, the Middle Jurassic Luobusa ophiolite of definite suprasubduction origin (Hébert et al. 2000; Hébert et al. 2001) is associated with Middle to Late Jurassic Zedong arc volcanics (Aitchison et al. 2004; McDermid 2002; McDermid et al. 2002). In contrast, the age-equivalent Spontang ophiolite (U-Pb age of 177±1 Ma, Pedersen et al. 2001; and K-Ar age of 169±9.5 Ma, Reuber et al. 1989) is interpreted as having originated under a mid-ocean ridge, and the age of the associated Spong island arc volcanics atop the ophiolitic pile is as young as middle Late Cretaceous, 88±5 Ma (Corfield et al. 2001; Pedersen et al. 2001). Some mid-Cretaceous ages obtained for the Spontang ophiolite (K-Ar ages of between 127 – 139 Ma, Reuber et al. 1989; and ^{39}Ar/^{40}Ar ages of between 124 – 130 Ma, Mahéo et al. 2004) are inferred to correspond to partial melting and metasomatism in a suprasubduction zone setting (Mahéo et al. 2004). Nonetheless, these age relationships indicate that this subduction magmatism was initiated at ca 130 Ma, notably later than the onset of the Zedong arc volcanism. Therefore, the development of the paired units, Luobusa-Zedong and Spontang-Spong, cannot be linked to the same intra-oceanic subduction. Instead, the latter pair corresponds to the development of the subduction system manifested by the Nidar and Dazhuqu ophiolites.

MODELS FOR THE CLOSURE OF TETHYS

Models of two categories can be further considered: 1) all the ophiolites developed in association with the same intra-oceanic subduction system; and 2) at least two subduction systems once existed within the closing Tethys. The first model assumes a long-lived subduction of the same slab of oceanic lithosphere, commencing in the Middle Jurassic (ca 177 Ma) and lasting for 120 myr until the intra-oceanic arc system collided with the Indian subcontinent in the Paleocene (ca 57 Ma, Ali and Aitchison 2005). This scenario was favored by McDermid (2002) because only one slab associated with intra-Neotethyan subduction is evident in the model for the closure of Neotethys based on seismic tomographic imagery (Van der Voo et al. 1999). If such was a case, the different phases of ophiolite generation might have occurred in different settings (forearc to backarc) within the suprasubduction zone environment. Ophiolite generation may have evolved in the process of subducting slab rollback, like in the modern Izu-Bonnin-Mariana subduction system (Bloomer et al. 1995). Further investigation is required to resolve the detailed setting for each particular ophiolite.

The other possible model (text-fig. 8) invokes existence of at least

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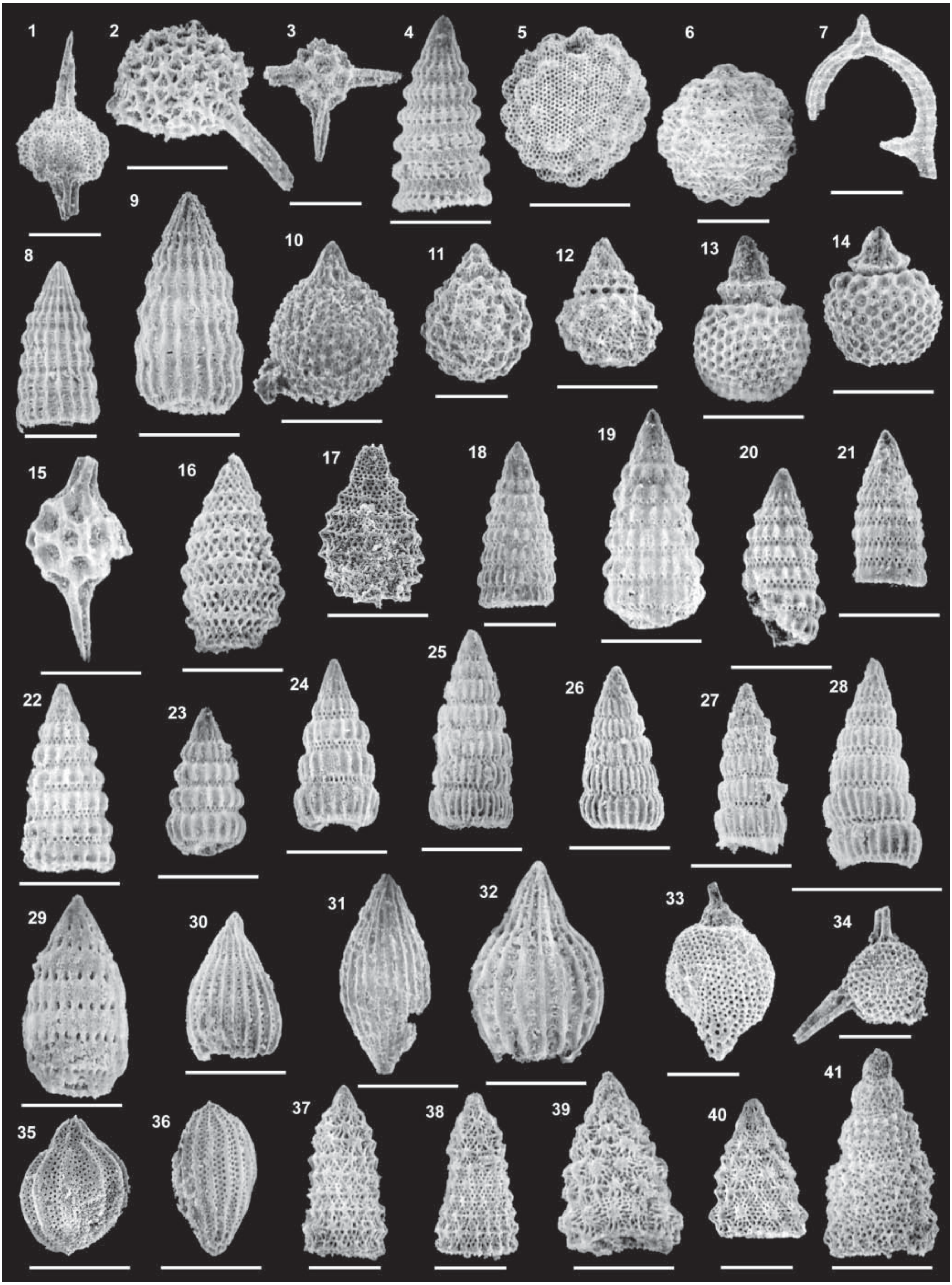
TEXT-FIGURE 5

Radiolarians from the Nidar ophiolite (scale bar = 100μm).

1 *Acaeniotyle umbilicata* (Rüst),
2 *Becus jiangzeensis* (Wu and Li),
3 *Cecrops septemporatus* (Parona),
4 *Crolanium puga* (Schaaf),
5-6 *Cryptamphorella clivosa* (Aliev),
7 *Dicerosaturnalis amissus* (Squinabol),
8-9 *Dictyomitra communis* (Squinabol),
10-11 *Hiscocapsa grutterinki* (Tan),
12 *Hiscocapsa kaminogoensis* (Aita),
13-14 *Hiscocapsa uterculus* (Parona),
15 *Pantanellium lanceola* (Parona), 1
16 *Parvicingula boesii* (Parona),
17 *Parvicingula usotanensis* Tumanda,
18-21 *Pseudodictyomitra carpatica* (Lozyniak),
22-24 *Pseudodictyomitra hornatissima* (Squinabol),
25-26 *Pseudodictyomitra lodogaensis* Pessagno,
27-28 *Pseudodictyomitra pentacolaensis*Pessagno,
29 *Pseudodictyomitra nuda* (Schaaf),
30 *Thanarla brouweri* (Tan),
31 *Thanarla lacrimula* (Foreman),
32 *Thanarla pacifica* Nakaseko & Nishimura,
33 *Syringocapsa agolarium* Foreman,
34 *Triactoma echiodes* Foreman,
35-36 *Turbocapsula costata* (Wu),
37-38 *Xitus alievi* (Foreman),
39-40 *Xitus clava* (Parona),
41 *Xitus spicularius* (Aliev).

9, 10, 15, 16, 18 – sample NDC-16; 29 – sample NDC-21; 1, 2, 7, 13, 14, 17, 21, 23 – sample NDC-23; 3, 5 – sample NDC-27; 6, 8, 11, 12, 32, 34, 37, 38, 39 – sample NDC-29; 4, 22, 30, 40 – sample NDC-52; 35 – sample NDC-58; 20, 23, 24, 36 – sample NDC-76; 19, 31 – sample NDC-83; 27, 28 – sample NDC-122; 41 – sample NDC-123; 25, 26 – sample NDC-160.

Text-figure 5



two subduction systems within the closing Tethys. The older system, remnants of which are represented by the Luobusa ophiolite and Zedong arc, was initiated in the Middle Jurassic (177 Ma) with the ophiolite generation above a subduction zone. This gave way to Middle to Late Jurassic arc volcanism (164 – 152 Ma, McDermid 2002; McDermid et al. 2002). The younger intra-Tethyan subduction system is marked by the Nidar and Dazhuqu ophiolites and the Dras volcanic arc. Ophiolite generation in the

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TEXT-FIGURE 6

Radiolarians from the Dazhuqu terrane (scale bar = 100μm). Re-produced from Ziabrev et al. 2003, with a kind permission of the Geological Society of London.

1 *Acaeniotyle umbilicata* (Rüst),

2 *Acaeniotyle diaphorogona* Foreman,

3 *Aurisaturnalis carinatus* (Foreman),

4 *Becus helenae* (Schaaf),

5 *Becus jiangzeensis* (Wu & Li),

6 *Becus horridus* (Squinabol),

7 *Cecrops* sp. cf. *C. septemporatus* (Parona),

8 *Crolanium puga* (Schaaf),

9 *Crucella euganea* (Squinabol),

10 *Crucella gavalai* O'Dogherty,

11 *Crucella hispana* O'Dogherty,

12 *Cryptamphorella clivosa* (Aliev),

13 *Cryptamphorella crepida* O'Dogherty,

14 *Cyclastrum infundibuliforme* Rüst,

15 *Dactyliodiscus lenticulatus* Jud,

16 *Dactyliosphaera maxima* (Pessagno),

17 *Deviatus diamphidius* (Foreman),

18 *Dicerosaturnalis amissus* (Squinabol),

19 *Dictyomitra communis* (Squinabol),

20 *Dictyomitra excellens* (Tan),

21 *Godia decora* (Li & Wu),

22 *Hexapyramis pantanellii* Squinabol,

23 *Hiscocapsa asseni* (Tan),

24 *Hiscocapsa grutterinki* (Tan),

25 *Hiscocapsa kaminogoensis* (Aita),

26 *Hiscocapsa orca* (Foreman),

27 *Hiscocapsa uterculus* (Parona)

28 *Obeliscoites perspicuus* (Squinabol),

29 *Obeliscoites vinassai* (Squinabol),

30 *Pantanellium lanceola* (Parona),

31 *Parvicingula boesii* (Parona),

32 *Parvicingula usotanensis* Tumanda,

33 *Podobursa tytthopora* (Foreman),

34 *Pseudoaulophacus* (?) *florealis* Jud,

35 *Pseudodictyomitra carpatica* (Lozyniak),

36 *Pseudodictyomitra hornatissima* (Squinabol),

37 *Pseudodictyomitra leptoconica* (Foreman),

38 *Pseudodictyomitra lilyae* (Tan),

39 *Pseudodictyomitra pentacolaensis* Pessagno,

40 *Pseudoeucyrtis hanni* (Tan),

41 *Stichomitra communis* Squinabol,

42 *Stichomitramediocris* (Tan),

43 *Thanarla brouweri* (Tan),

44 *Thanarla carboneroensis* O'Dogherty,

45 *Thanarla lacrimula* (Foreman),

46 *Thanarla pacifica* Nakaseko & Nishimura,

47 *Thanarla pseudodecora* (Tan),

48 *Torculum bastetani* O'Dogherty,

49 *Triactoma hybum* Foreman,

50 *Trisyringium capellinii* Vinassa,

51 *Turbocapsula costata* (Wu),

51 *Ultranapora praespinifera* Pessagno,

53 *Xitus alievi* (Foreman),

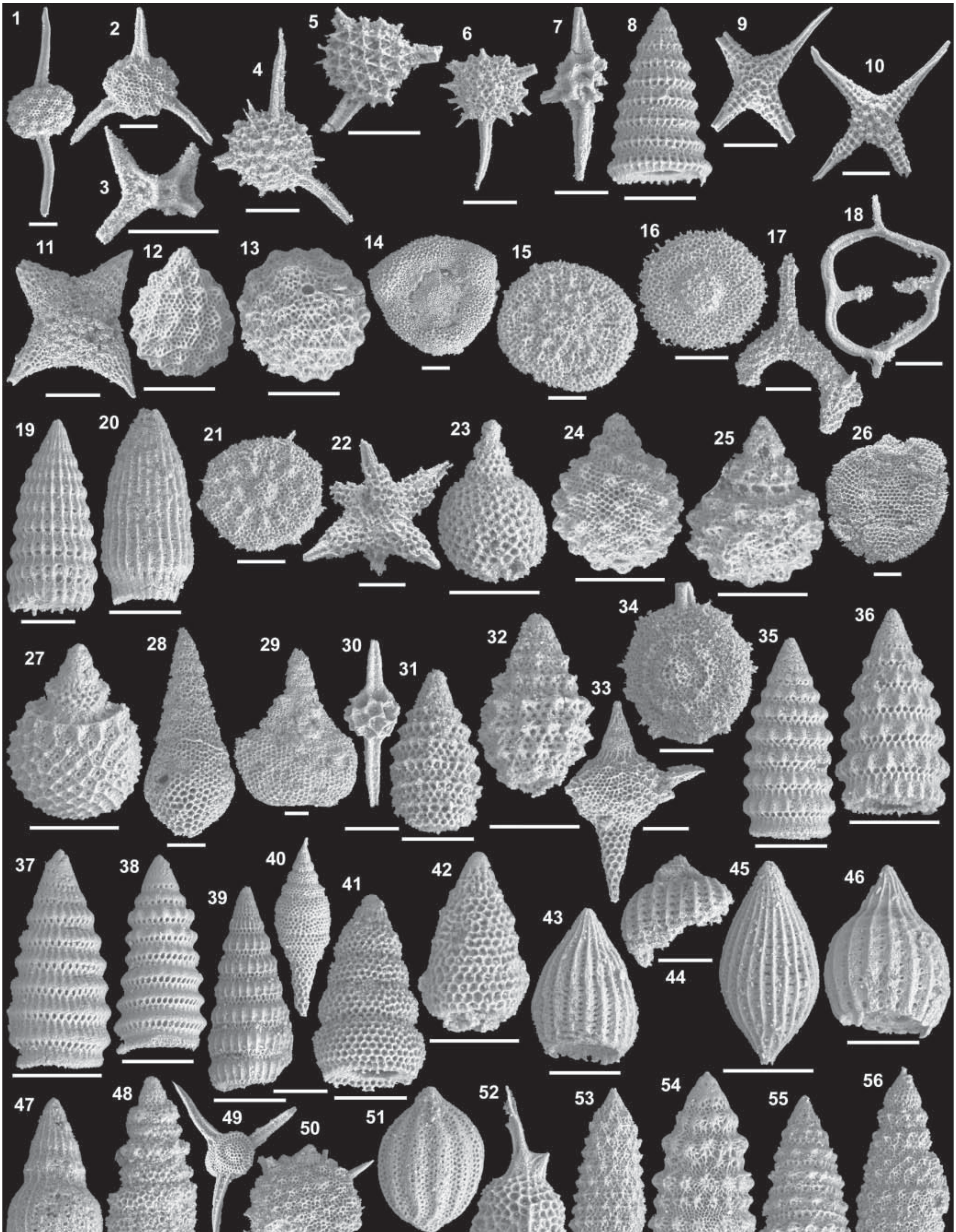
54 *Xitus clava* (Parona),

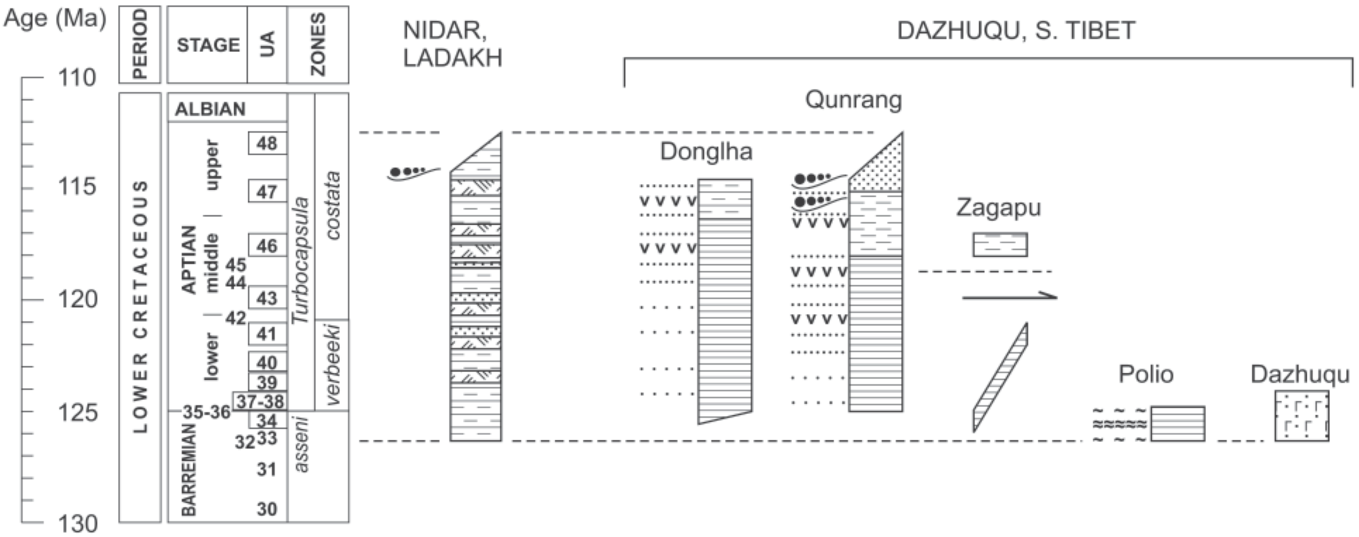
55 *Xitus elegans* (Squinabol),

56 *Xitus spicularius* (Aliev).

4, 28, 53 – sample SZ-98-Do-4; 13 – sample SZ-98-Do-6; 24 – sample SZ-98-Do-7; 9, 10, 43, 48, 52, 54, 55 – sample SZ-98-Do-8; 6, 50 – sample SZ-98-Do-11; 1, 15, 16, 18, 21, 49 – sample SZ-98-Do-16; 11, 51 – sample SZ-98-Do-19; 31 – sample SZ-98-Q-1; 3, 14, 17, 19, 20, 23, 30, 33, 44, 45, 47 – sample SZ-98-Q-4; 40 – sample SZ-98-Q-6; 42 – sample SZ-98-Q-7; 39, 41, 56 – sample SZ-98-Q-19; 8 – sample SZ-98-Q-20; 2, 22, 29 – sample SZ-99-ZD; 5, 25, 26, 46 – sample SZ-98-P-7; 7, 12, 27, 32, 34, 35, 36, 37, 38 – sample SZ-98-D-4.

Text-figure 6





TEXT-FIGURE 7
Correlation chart of the Nidar and Dazhuqu sedimentary sections with lithologies plotted against biostratigraphic (modified from O'Dogherty, 1994 and O'Dogherty and Guex 2002) and chronostratigraphic (after Gradstein et al. 2004) scales. Non-horizontal boundaries indicate uncertainties in age. For key see text-figure 4.

supra-subduction zone setting took place in the Cretaceous, late Barremian (ca 126 Ma) and was followed by the onset of extrusive arc volcanism by early Aptian (ca 124 Ma). The volcanic arc was active throughout the Cretaceous (Reuber 1989; Reuber et al. 1989) until it collided with the Asian continent in the west at ca 75 Ma, and with the Indian subcontinent in the east at ca 57 Ma. This implies that the Cretaceous intra-oceanic subduction system was oblique to the Asian continental margin subduction system. Such relations are discernable from a seismic tomographic imagery of the associated oceanic slabs underneath India, especially for the depths of 1500km and 1900km (Van der Voo et al. 1999, fig. 5f-g). However, the original disposition of the older and younger intra-Tethyan subduction systems remains unresolved. It is possible that the former lay well south with respect to the latter and was the first to collide with India. Alternatively, it might have collided with the younger accretionary system prior to collision with India (text-fig. 8).

A more complex evolutionary scenario for the closure of the Ladakh sector of Tethys assumes the existence of two volcanic arcs (Dras and Spong) that developed in association with two separate intra-oceanic subduction zones during the late Early to Late Cretaceous (Corfield et al. 2001; Pedersen et al. 2001). In this model, the Dras arc docked with Asia whereas the Spong arc, that lay to the south, was emplaced onto the Indian northern margin prior to the India-Asia collision. Although the Spontang ophiolite and Spong arc are differentiated as components of yet another intra-Tethyan subduction system (Corfield et al. 2001; Pedersen et al. 2001), they might belong to the Nidar-Dras system as the ophiolite alteration in a suprasubduction zone setting at ca 124 Ma (Mahéo et al. 2004) was synchronous to the generation of the Nidar ophiolite.

CONCLUSIONS

Recalibration of radiolarian ages and revised biostratigraphic correlation of marine sedimentary successions of the Nidar and Dazhuqu ophiolites reveals their equivalent upper Barremian to upper Aptian (mid-Cretaceous) stratigraphic ranges. Both successions also contain a similar record of arc volcanism. Given that the Nidar section is tectonically truncated at the base, the lower limit of its stratigraphic range places a minimum temporal constraint on the timing of the ophiolite generation as late Barremian. This compares well with radiometric ages and likely indicates the timing of the ophiolite generation. The Nidar and Dazhuqu ophiolites are interpreted as distant chronological equivalents that developed in association with the same intra-Tethyan volcanic arc. Related Dras island arc volcanism in the Nidar section began in the early Aptian. Parallels in the evolution of this Cretaceous intra-Tethyan subduction system with other systems in the region are uncertain.

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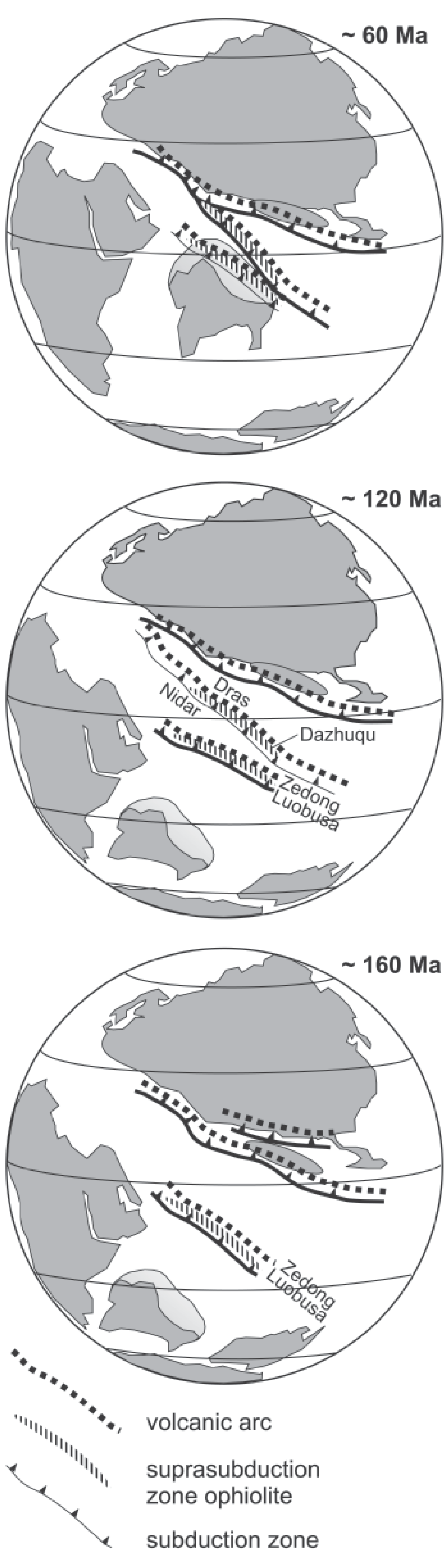
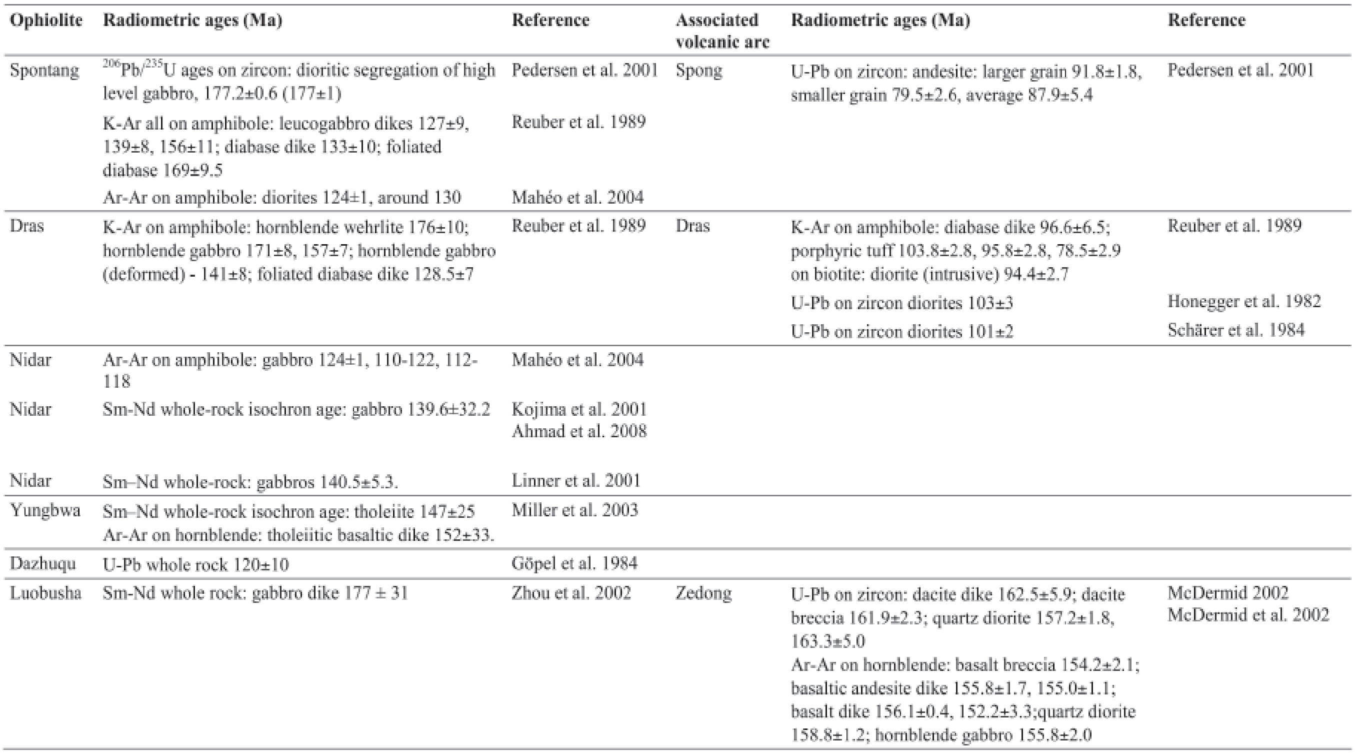


TEXT-FIGURE 8
Possible evolutionary scenario for the closure of Tethys.

TABLE 1
Radiometric ages of the ophiolites and associated volcanic arc rocks distributed along the Indus – Yarlung-Tsangpo suture zone.



Ophiolite	Radiometric ages (Ma)	Reference	Associated volcanic arc	Radiometric ages (Ma)	Reference
Spontang	^{206}Pb/^{235}U ages on zircon: dioritic segregation of high level gabbro, 177.2±0.6 (177±1)	Pedersen et al. 2001	Spong	U-Pb on zircon: andesite: larger grain 91.8±1.8, smaller grain 79.5±2.6, average 87.9±5.4	Pedersen et al. 2001
	K-Ar all on amphibole: leucogabbro dikes 127±9, 139±8, 156±11; diabase dike 133±10; foliated diabase 169±9.5	Reuber et al. 1989			
	Ar-Ar on amphibole: diorites 124±1, around 130	Mahéo et al. 2004			
Dras	K-Ar on amphibole: hornblende wehrlite 176±10; hornblende gabbro 171±8, 157±7; hornblende gabbro (deformed) - 141±8; foliated diabase dike 128.5±7	Reuber et al. 1989	Dras	K-Ar on amphibole: diabase dike 96.6±6.5; porphyric tuff 103.8±2.8, 95.8±2.8, 78.5±2.9 on biotite: diorite (intrusive) 94.4±2.7	Reuber et al. 1989
				U-Pb on zircon diorites 103±3	Honegger et al. 1982
				U-Pb on zircon diorites 101±2	Schärer et al. 1984
Nidar	Ar-Ar on amphibole: gabbro 124±1, 110-122, 112-118	Mahéo et al. 2004			
Nidar	Sm-Nd whole-rock isochron age: gabbro 139.6±32.2	Kojima et al. 2001 Ahmad et al. 2008			
Nidar	Sm–Nd whole-rock: gabbros 140.5±5.3.	Linner et al. 2001			
Yungbwa	Sm–Nd whole-rock isochron age: tholeiite 147±25 Ar-Ar on hornblende: tholeiitic basaltic dike 152±33.	Miller et al. 2003			
Dazhuqu	U-Pb whole rock 120±10	Göpel et al. 1984			
Luobusha	Sm-Nd whole rock: gabbro dike 177 ± 31	Zhou et al. 2002	Zedong	U-Pb on zircon: dacite dike 162.5±5.9; dacite breccia 161.9±2.3; quartz diorite 157.2±1.8, 163.3±5.0 Ar-Ar on hornblende: basalt breccia 154.2±2.1; basaltic andesite dike 155.8±1.7, 155.0±1.1; basalt dike 156.1±0.4, 152.2±3.3;quartz diorite 158.8±1.2; hornblende gabbro 155.8±2.0	McDermid 2002 McDermid et al. 2002

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TABLE 2
Occurrence of radiolarian species in the Nidar and Dazhuqu sedimentary sections.

ophiolite, region	NIDAR, LADAKH														DAZHUQU, S. TIBET																																														
sample number	NDC-														SZ-98-Do-																			SZ-98-Q-														SZ-99		SZ-98-P-											SZ-98-D-4
species list	16	20	21	23	27	29	52	58	60	76	83	122	123	160	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	1	3	4	5	6	7	8	9	14	15	18	19	20	21	-Z-B	-Z-D	2	3	4	5	6	7	8	9	12	14	15	
Acaeniotyle diaphorogona Foreman																+	+		+	+	+	+	+	+	+	+	+		+	+	+	+	+			+	+	+											+	+	+		+			+					+
Acaeniotyle umbilicata (Rüst)				+		+	+	+							+	+	+		+	+	+	+	+	+	+	+	+		+	+	+	+	+	+		+	+	+	+						+	+			+	+	+		+		+			+	+	+	+
Aurisaturnalis carinatus (Foreman)																																		+	+	+																								
Becus helenae (Schaaf)																+	+			+	+	+	+			+	+		+	+			+			+															+									+	
Becus jiangzeensis (Wu & Li)			+	+		+												+																		+														+	+		+	+	+	+	+	+	+	+	+
Becus horridus (Squinabol)																							+	+	+		+		+	+	+	+																												
Cecrops septemporatus (Parona)	+		+		+																																																								+
Crolanium puga (Schaaf)	+		+			+	+													+	+		+	+	+	+	+	+		+	+	+	+			+	+	+								+		+	+	+	+	+	+		+		+			+	+
Crucella bossoensis Jud																																				+														+								+		
Crucella euganea (Squinabol)																					+	+	+	+	+	+	+		+	+	+	+	+																+												
Crucella gavalai O'Dogherty																		+	+	+	+	+			+	+	+																																	
Crucella hispana O'Dogherty																															+	+	+						+	+	+		+						+												
Cryptamphorella clivosa (Aliev)				+		+									+	+	+	+	+		+	+					+	+	+	+	+			+	+	+		+	+										+	+	+	+	+		+		+		+	+	+
Cryptamphorella crepida O'Dogherty															+				+																		+																					+		+	
Cryptamphorella gilkeyi (Dumitrica)																																																+													
Cyclastrum infundibuliforme Rüst																																				+																								
Dactyliodiscus lenticulatus Jud																	+	+				+	+	+	+	+		+	+		+		+			+	+			+																				+	
Dactyliosphaera maxima (Pessagno)																						+		+				+	+	+	+	+	+																											
Deviatus diamphidius (Foreman)																				+		+	+	+			+						+			+													+		+								+		
Dicerosaturnalis amissus (Squinabol)				+													+	+		+	+	+	+	+	+	+			+	+	+					+															+				+					+	+
Dictyomitra communis (Squinabol)	+	+	+	+		+	+			+					+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+		+	+	+	+	+	+	+	+	+	+	+		+	+	+	+	+
Dictyomitra excellens (Tan)																				+																+																								
Godia concava (Li & Wu)																													+							+																								
Godia coronata (Tumanda)																																				+																								
Godia decora (Li & Wu)																					+	+	+	+	+	+	+	+	+	+	+	+	+						+	+	+								+												
Godia florealis (Jud)																+																		+	+	+																	+							+	+
Hexapyramis pantanellii Squinabol																								+																	+								+												
Hiscocapsa asseni (Tan)															+				+	+	+	+		+				+			+			+		+		+													+								+	+	
Hiscocapsa grutterinki (Tan)	+					+														+				+				+																						+			+							
Hiscocapsa kaminogoensis (Aita)						+																																												+				+						+
Hiscocapsa orca (Foreman)																	+																	+																		+	+	+		+	+			
Hiscocapsa uterculus (Parona)	+		+	+																																+												+			+		+	+							+
Obeliscoites perspicuus (Squinabol)																	+							+						+				+							+						+														
Obeliscoites vinassai (Squinabol)																				+																												+												
Pantanellium lanceola (Parona)	+																			+							+							+	+	+	+													+	+				+			+	+	+	
Parvicingula boesii (Parona)	+					+																												+	+													+		+	+		+	+	+		+	+			+
Parvicingula usotanensis Tumanda		+	+	+																														+	+																		+								+
Podobursa typica (Rüst)																				+																+															+		+						+		
Podobursa tytthopora (Foreman)																																		+		+																			+					
Pseudodictyomitra carpatica (Lozyniak)	+			+		+	+		+	+	+				+		+		+															+	+	+	+	+										+		+		+	+	+	+	+	+	+	+	+	+
Pseudodictyomitra hornatissima (Squinabol)						+	+			+	+		+			+				+	+	+		+	+	+	+		+	+	+	+	+	+	+			+	+	+	+	+	+		+	+	+			+	+	+	+		+						+
Pseudodictyomitra lodogaensis Pessagno												+	+	+																																														
Pseudodictyomitra nuda (Schaaf)	+		+																	+																																								
Pseudodictyomitra pentacolaensis Pessagno												+																				+												+	+	+	+														
Pseudoeucyrtis apochrypha O'Dogherty																																																	+											
Pseudoeucyrtis hanni (Tan)															+	+	+			+	+		+	+	+	+	+	+	+		+	+	+	+		+		+		+	+		+				+		+	+	+								+		+
Spongostichomitra elatica (Aliev)																																									+						+													
Staurosphaeretta longispina (Squinabol)																										+				+		+																												
Stichocapsa ? pulchella (Rüst)																																																			+									
Stichomitra communis Squinabol																						+																+							+	+														
Stichomitra japonica (Nakaseko & Nishimura)																					+															+																								
Stichomitra mediocris (Tan)																				+	+	+	+																+																					
Syringocapsa agolarium Foreman				+																																																								+
Thanarla brouweri (Tan)							+								+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+		+			+	+	+	+	+	+			+	+	+		+			+			+	+
Thanarla carboneroensis O'Dogherty																																		+		+																								
Thanarla lacrimula (Foreman)											+				+	+	+	+	+	+														+	+	+	+	+										+		+	+		+		+				+	+	+
Thanarla pacifica Nakaseko & Nishimura	+	+				+									+	+	+	+	+	+							+							+	+	+	+	+										+		+	+	+	+	+	+	+		+			
Thanarla pseudodecora (Tan)															+		+																	+	+	+	+														+								+	+	
Torculum bastetani O'Dogherty																					+	+	+	+	+	+	+	+	+	+	+	+	+									+							+												
Triactoma echiodes Foreman						+														+	+	+		+	+	+			+	+					+																+					+					+
Triactoma hybum Foreman																	+			+	+	+	+	+	+	+	+		+	+						+		+												+										
Trisyringium capellinii Vinassa																								+		+			+																			+												
Turbocapsula costata (Wu)							+	+		+										+				+	+	+			+	+	+	+	+						+	+	+				+	+			+												
Ultranapora praespinifera Pessagno																				+	+	+		+	+	+	+	+	+	+	+	+	+			+					+																			
Xitus alievi (Foreman)						+									+	+	+	+	+															+	+	+	+													+	+		+		+			+			+
Xitus clava (Parona)	+		+	+	+	+	+								+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+				+	+		+	+	+	+	+	+	+	+			+		+	+
Xitus elegans (Squinabol)																	+	+	+	+	+	+	+	+		+	+	+	+			+						+						+										+	+					+	+	
Xitus spicularius (Aliev)													+																															+	+				+												
Zhamoidellum leiostraca (Foreman)																																																						+					
Zhamoidellum trachyostraca (Foreman)																																																	+	+										

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